

Developing Sustainable Life Support System Concepts

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Sustainable spacecraft life support concepts may allow the development of more reliable technologies for long duration space missions. Currently, life support technologies at different levels of development are not well evaluated against each other, and evaluation methods do not account for long term reliability and sustainability of the hardware. This paper presents point-of-departure sustainability evaluation criteria for life support systems, that may allow more robust technology development, testing and comparison. An example sustainable water recovery system concept is presented.

I. Introduction

Sustainability is the capacity to endure. Long duration spaceflight, as anticipated for Moon and Mars missions, will require hardware that is less prone to failure and generally more rigorous and sustainable than the current state-of-the-art. Sustainable Environmental Control and Life Support Systems (SECLSS) may be developed to function for long periods of time in harsh environments, with limited maintenance and resupply. Water recovery, air revitalization, habitation, food and power systems may benefit from considering sustainability a design goal.

The SECLSS project is designed to develop rough life support system architectures, evolve technology concepts, and collaborate with NASA partners to consider long term sustainability as a design driver for life support systems. One example application requiring innovation is wastewater management, wherein wastewater fouling is accommodated by the design of the fluid management hardware. This paper provides an overview of the SECLSS project concept and proposed sustainability evaluation criteria for ECLSS technologies, and details a preliminary example technology for water recovery on the lunar outpost.

II. Background

A long-term lunar outpost will require sustainable life support technologies that are capable of functioning for years with minimum resupply and maintenance. While life support resources such as water and air will remain in short supply, the availability of gravity, energy, and natural resources on the lunar surface allow for innovation in the design of outpost technologies, potentially including the adoption of terrestrial technologies previously not feasible for short duration microgravity flight.

As missions become extended in duration and move toward more self-reliant operations, new demands are placed on the life support system design. Thus far, all indications have suggested that the lunar outpost water recovery systems will be evolved from current spacecraft technologies, including urine pretreatment and distillation¹. However, these technologies were developed for microgravity compatibility, and may carry undesirable fouling and failure mode heritage from this environment. For example, it is well recognized that water handling systems used in a spacecraft are prone to failure caused by biofouling and mineral scaling, which can clog mechanical systems and degrade the performance of capillary-based technologies. The recent challenges with the Urine Processing Assembly on the International Space Station point to urine precipitate fouling of the mechanical hardware.

III. Sustainable ECLSS Concepts

The concepts packaged within the Sustainable ECLSS project are not new. Spacecraft engineers have always been concerned with reliability, maintainability, robustness and performance. However, competing requirements and mechanisms of technology development have sometimes resulted in programs focusing on existing, complex technologies that have evolved for specific reasons and constraints. These technologies may, in fact, not be particularly sustainable or appropriate for longer duration space missions. Instead, the original constraints and requirements can be reevaluated based on actual expected mission conditions, and technology development can be

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integrated with other architecture considerations appropriate for the expected mission profile. For example, a life support technology developed for the microgravity environment on the International Space Station may or may not be appropriate for a similar use on a planetary outpost, particularly when the hardware is necessarily complex to manage fluids in microgravity. A partial gravity environment can allow for dramatic simplification of the technology, and likely improvement in sustainability.

ECLSS subsystems are often evaluated using Equivalent System Mass (ESM), which sums the real mass of a system with mass penalties for volume, power, cooling, crewtime and logistics. However, ESM does not currently directly account for reliability and other sustainability considerations, and instead assumes a similar level of potential failures between technologies.

The developers of ESM state, “Ideally, an effort should be made to adjust the design of subsystems or systems in order to bring them to similar levels of potential failures ... an effort should be made to design subsystems to similar levels of reliability by taking into account the mean time before failure. In reality, a lack of data may prevent ESM from accounting for reliability and safety specifications ... If this is the case, the researcher’s expertise on the matter may then be used to make reasonable adjustments in ESM in order to compare technologies.”²

Therefore, ESM inherently relies on the technology developers to provide candid input on reliability, and requires operational experience to evaluate failures. ESM has no mechanism to compare technologies at different Technology Readiness Levels (TRL), and as such currently has limited capability to allow the evaluation of a range of potential technologies. ESM also assumes that the technologies meet identical reliability and technical requirements, “Comparison of systems or subsystems with ESM is only suitable where the systems or subsystems satisfy identical requirements, including levels of safety and reliability.”²

Other technology and architecture developers have struggled with these same limitations in evaluating state-of-the-art alongside promising technologies, “ESM is the sum of real masses and mass penalties for cost factors judged to be significant for life support: volume, power, cooling, manpower, and logistics. ... Thus it does not consider flight readiness (TRL) nor requirements options. It is taken as a given that capacity and safety requirements are met, and that whatever is necessary to keep the system running for the duration of the mission (e.g. spares, makeup gas, crew time) is included in ESM.”³

These assumptions of TRL and reliability are at the very least limiting for ESM evaluations. This paper proposes a point of departure for adding sustainability criteria to ESM calculations that may allow the comparison of technologies at different TRLs, and may identify commonalities and best practices to enable the development of more sustainable ECLSS technologies.

As an inspiration for these criteria, the United States Green Building Council Leadership in Energy and Environmental Design (LEED) Green Building Rating System is used as an example. LEED was designed to standardize environmental sustainability evaluation criteria for new and remodeled buildings. The LEED concept uses a point-based system to award a score to a design based on several categories, including site selection, water use, energy use, materials selection, indoor air quality, and use of innovative technologies, and consideration of local conditions. Using this evaluation tool as a guide, the criteria listed below are proposed for integration with ESM calculations. The author fully recognizes that these are only points of departure, and the tabulated points presented are for discussion purposes only. The intent is to encourage a discussion of sustainable practices for ECLSS technologies.

I. Simplest Feasible Design

Striving for simplicity in design is an ancient engineering goal. Spacecraft system engineers are trained no differently. However, programmatic considerations often drive technology to more complex, and therefore often less sustainable, configurations. Unfortunately, there is not often a strong push-back against this progression. It is suggested here that criteria can be standardized to evaluate a technology as being the most simplified design that complies with appropriate requirements. An initial representation of these criteria is presented below.

- a. **Appropriate Requirements** – The process of developing hardware requirements is necessarily inclusive of many stakeholders, who each have their own niche considerations. However, because of this, project requirements can become unwieldy, requiring technology to grow in complexity to respond to all requirements. Therefore, it is suggested that program managers work with project managers to regain control over requirements creep and develop process authority to reject unnecessary requirement burdens. Technologies that successfully simplify their requirements will likely be more sustainable.

- b. **Complexity** - The engineering complexity of a subsystem is often driven by design requirements. However, complexity also often results in increasing likelihood of debilitating failures. By identifying hardware complexity separately from performance, a more comprehensive understanding of mission capability may be developed.
- c. **Reliance on Controlled Operating Conditions** - Performance and operational requirements drive subsystem design. Engineers appreciate well defined requirements that allow the development of technologies with high confidence that they will meet defined requirements. However, the more narrowly defined the requirements, the more likely that the operational environment will exceed the requirements. Therefore, it is appropriate to evaluate how reliant a design is on tightly controlled requirements, and if the system can accommodate a broader range of operational conditions. For example, some wastewater management technologies rely on minimal performance variation of oxidizing pretreatment chemicals. Should the pretreatment fail to prevent wastewater fouling, some technologies will degrade significantly and may fail. However, other designs may allow for accommodation of such conditions.
- d. **Dissimilar Redundancy and Degraded Performance** – When expected and unexpected failure modes manifest themselves during flight, redundancies are expected to allow the safe execution of the mission. The capacity for technology manifest unexpected failures suggests that dissimilar redundancies, including technologies that may offer a lower level of performance, may be a valuable approach. Similarly, technologies that can offer degraded but non-zero performance may prevent emergencies.
- e. **Integration** – Comprehensive and thoughtful consideration by architecture and technology developers upstream of hardware builds can prevent integration issues, where one technology is wholly dependent on another’s performance. Likewise, thorough understanding of the range of inputs to be expected by, and outputs expected of, the technology may result in more robust performance.
- f. **Uptime x Key Performance Parameter (KPP)** - Designs are often driven to higher performance standards. However, higher performance may also yield more complex and failure-prone designs. Therefore it is important to consider both performance and uptime. The factor of uptime percent to the functional key performance parameter percent may be an appropriate tool to compare technologies. For example, is a water recovery system with 90% recovery that has 60% uptime better or worse for the mission than a system with 80% recovery but a 90% uptime (0.54 factor vs. 0.72)?
- g. **TRL x Critical Failure Frequency (CFF)** - Technology Readiness Level (TRL) is used as an approximation of the maturity of a given design. The general assumption is made that higher TRL level systems are more reliable and “validated”. However, as illustrated by other parameters and examples listed here, higher TRL level technologies do not necessarily result in more robust or appropriate technologies. Therefore, caution should be taken to appropriately consider TRL when comparing technologies against one another. One potential way of evaluating the true value of a higher TRL technology is to multiply the TRL by the frequency of debilitating failures. This will better allow the sustainability of technologies at different TRLs to be compared. For example, if a TRL 9 technology, that is ostensibly flight-proven, has a failure taking the system out of service twice a year, then the TRL x CFF factor is 18. In contrast, a laboratory-based proof of concept TRL 6 technology that has a failure every three months of components under test would have a TRL x CFF factor of 24. However, should this system have failures only twice a year, then the TRL x CFF would be 12. The lower the TRL x CFF factor, the higher the likelihood of a sustainable, robust design.

II. High Fidelity Environmental Testing

In addition to the technical design considerations, it is possible that more sustainable spacecraft fluid management technologies might also be developed by reconsidering the methods in which they are typically tested under highly controlled conditions. The goal is generally to conduct defined tests that produce predictable and reproducible results akin to how basic scientific research is carried out. Once these systems are in space, however,

they often fail in complex, unforeseen ways leaving engineers consumed with troubleshooting and the systems in disuse.

Designing, testing and evaluating spacecraft life support systems is an engineering challenge more than it is a basic science research challenge. Rather than examining fundamental processes, engineers are generally more interested in how well a given system meets operational requirements. Testing protocols, therefore, should be adjusted to reflect this goal. Systems should not need to be fully characterized under precise and controlled environments; rather results from complex and compounded conditions within defined boundaries should be compared to stated performance requirements. Suggested basic elements of this approach are:

1. Set performance requirements and evaluation criteria for desired technology
2. Define reasonable envelope of expected operational environmental conditions
3. Evaluate multiple technologies within this expected operational envelope
4. Escalate, expand and compound the envelope as technologies mature
5. Evaluate the results against performance requirements and technology capabilities

While this approach may seem like standard engineering practice, it is in fact a departure from the methods in which most spacecraft life support systems are tested, perhaps a consequence of the rarity and expense of ‘in-space’ field testing. Specifically, the typical approach today is to control the testing environment in such a way that any particular requirement is evaluated in relative isolation. For example, ground tests with fluid systems often use ersatz with over-simplified conditions that do not fully represent the actual environment that produces the appropriate complex surface conditions in which the fouling occurs. Engineering performance tests consequently should be less concerned with fully characterizing a single parameter in favor of gaining confidence in the system’s overall robustness and sustainability across a range of expected conditions.

This approach will result in more sustainable spacecraft life support systems. Through designing, testing and evaluating technologies based on the truly complex environments they will be exposed to, designers can introduce methods that will enable technologies to be more robust, easily maintained, and recoverable. For example, a system need not be designed for the worst-case scenario in each direction of the environmental envelope, as long as the system can recover from degraded performance. Should a spike in a particular condition cause a failure or degraded performance, the system should be able to both a.) identify that an alarm condition has occurred, and b.) allow for recovery to operational performance with minimal consumable or crew cost. Additionally, by allowing engineers to design for end-of-life performance, the systems will have more predictable operational and maintenance characteristics. Several proposed evaluation criteria for the testing environment are proposed below:

- a. **Appropriateness for Environment** - Subsystems are initially driven by flight requirements. However, the long development profile of life support hardware can result in technologies that ultimately are not fully appropriate for their operational conditions. For example, adapting microgravity compatible technologies for the lunar surface may not be the most technologically appropriate solution, and may result in needlessly complex and failure prone hardware being used in an environment where simplified hardware could be used instead. An evaluation of the technology candidate for appropriateness in the operational environment may identify potential alternatives, improvements or simplifications.
- b. **Failure Types and History** - Development units, ground testing and flight operations identify component and system level issues that can range from nuisances to maintenance concerns to debilitating failures. The nature, impact and understanding of these failures can provide an important dimension to technology evaluation. For example, if a valve fails on a breadboard system in a lab, this may be an expected and well characterized failure. However, when a flight hardware systems fails because unexpected kinds of wastewater fouling have clogged a fluid management system, and this failure was not expected or well characterized, the fundamental design may be reevaluated.
- c. **Testing History and Rigor** - Engineering performance tests consequently should be less concerned with fully characterizing a single parameter in favor of gaining confidence in the system’s overall robustness and sustainability across a range of expected conditions.
- d. **Consumables** – Normally, designers and planners account for ELCSS consumables such as make-up gases, balance water, packaging, and on-orbit replacement units (ORUs), and add in additional margin. However, this planning does not account for off-nominal performance or unexpected failures. Because of this, the ESM calculation for consumables does not accurately reflect the dramatic increase in cost

associated with crewtime and emergency resupply. A more comprehensive understanding of technology robustness may yield a more accurate estimation of consumables.

These point-of-departure criteria are tabulated in Table 1, below, with sustainability points assigned for rough guides. It is suggested that a revised table could then be integrated with ESM calculations, with each point representing one kg of ESM.

Table 1. Potential Sustainability Parameters for Equivalent System Mass

Parameter	Evaluation Criteria	Sustainability Points (equivalent to ESM)
Simplest Feasible Design		
a. Appropriate Requirements	Evaluation by technology developers that requirements are simplified	+10
b. Complexity	Dynamic components	-1 per component
	Static control of fluids	+1 per fluid loop
c. Reliance on Controlled Operating Conditions	Independent evaluation of input/output assumptions from integrated hardware	-1 for each parameter defined within 10%
		+1 per parameter accommodated within 50%
d. Dissimilar Redundancy and Degraded Performance	Dissimilar redundancy capability	+10
	Capability to operated at degraded performance standard under simplified operating conditions	+10
e. Integration	Number of systems to be integrated	- 5 per system
f. Uptime x KPP	Use of KPP typical for similar systems	+ Factor x 10 points
g. TRL x CFF	Frequency of critical failures	(-) TRL x CFF
High Fidelity Environmental Testing		
a. Appropriateness for Environment	Increased complexity of design for microgravity compatibility when intended for planetary surface	- 10
	Consideration of all inputs and outputs to system	+10
b. Failure Types and History	Component Level	- 1
	System Level	- 5
	Fouling	- 5
	Anticipated Failures	- 1
	Unexpected Failures	- 5
	Return to operation without special tooling or resupply	+ 10
c. Testing History and Rigor	Appropriately defined environmental testing	+ 10
	Independent validation testing	+ 10
	Compliance with sustainable testing criteria	+ 10
d. Consumables	Anticipated consumables	+ 1 per component
	Unexpected replacement needs	- 5 per component
	Maintenance requirements	- # hours per year
	ISRU	+ 5 per use

IV. Example Sustainable Water Recovery System Concept

An example ECLSS technology category that may benefit from increased attention on sustainability are those systems that manage water and wastewater. Development of spacecraft life support hardware over the past few

decades has focused primarily on microgravity applications, with sophisticated designs usually constrained by limitations of volume, mass and power. In particular, for 2-phase gas/liquid separation in microgravity, centripetal acceleration or capillary action is used to remove liquids without the aid of gravity-driven buoyancy. These systems have often been prone to failure due to fluid fouling caused by biological reactions or mineral scaling, which can clog mechanical systems and degrade the performance of capillary-based systems. In turn, these failures can cause increased maintenance cost and overall crew labor burden.

Unlike orbiting spacecraft, a lunar outpost will exist in a fractional Earth gravity environment ($\sim 0.166g_0$) with abundant natural resources including lunar regolith, vast open surfaces, and plentiful sunlight. Gravity can at the very least make complex microgravity compatible technologies unnecessary, and at best be advantageously utilized in a wastewater recovery process. Meanwhile, the outpost may not have ready access to Earth resupply, making consumables and maintenance of greater concern when conducting design trade studies. Lunar surface conditions are perhaps more analogous to the terrestrial environment than to microgravity space flight. For these reasons, the appropriate technology development approach for lunar outpost hardware may likely be adapting terrestrial technologies for use in a hypo-gravity environment, rather than modifying microgravity space flight technologies.

Instead, the lunar outpost may consider using simple and robust terrestrial technologies such as media filters and solar disinfection and distillation to recover water, taking advantage of the ready availability of lunar regolith, gravity, and solar energy. Therefore, rather than stabilizing wastewater such as urine for disposal, the wastewater could be encouraged to foul the media and form biofilms and precipitates that can then be filtered and the water reclaimed for future use. This concept is detailed in a 2009 paper from this conference⁴.

V. Conclusion

Long duration space missions, such as expected for a Lunar Outpost or a Mars transit, will drive the need for hardware that is less prone to failure and generally more robust and sustainable. Currently, technology developers are constrained by complex requirements, operational environments, and development momentum. This can lead to technologies that are more complex than needed, less appropriate for the operational environment, and more prone to failure.

This paper presents point-of-departure sustainability evaluation criteria for ECLSS technologies that may, once refined, allow for the integration of sustainability criteria into ESM evaluations, and even allow ESM to be used for comparing technologies at different TRLs. This paper encourages readers to contribute to evolving these concepts and criteria.

Additionally, an example ECLSS water recovery technology is presented that may embody some of the sustainability criteria presented. This example, and others, should be further developed with collaborators to enable more robust, sustainable technologies. These technologies may draw on terrestrial applications, and likewise sustainable ECLSS technologies may be applied to life support challenges on Earth.

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